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Fine-Resolution Imaging of Solar Features Using Phase-Diverse Speckle: Annual Status Report

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In this first annual status report for NASA Grant Number NAGW-4069, we review the background for the research, describe the accomplishments of the first funding period (1 April through 31 December, 1994) of this two-year grant, list the presentations and publications delivered under this grant, and provide a brief description of the research planned in the second year of funding.

1. Background

Recall that *Phase-Diverse Speckle Imaging* (PDSI) is a novel imaging technique intended to overcome the degrading effects of atmospheric turbulence on fine-resolution imaging. As its name suggests, PDSI is a blend of phase diversity and speckle imaging concepts. A PDSI data set consists of a short-exposure image pair, one conventional (in focus) and one intentionally defocused (introducing phase diversity), for each of several atmospheric realizations. We use maximum-likelihood estimation to jointly estimate the object (common to all images) and a phase-aberration function for each atmospheric realization. Our goal under this grant is to develop PDSI for use in ground-based solar observing. The method is appealing because the optical hardware is simple and provides an alternative to adaptive optics, there is no need for a speckle-calibration step (which is needed for conventional speckle imaging but is problematic in solar observations), significantly fewer short-exposure images are required relative to conventional speckle imaging, and the method can be generalized to accommodate anisoplanatic effects.

2. First-Year Accomplishments

We were able to achieve a major milestone by successfully performing the first ever phase-diverse speckle reconstruction on real solar data. Several algorithmic developments were needed in order to achieve this important milestone. The first is the development of the algorithm to accommodate edge effects associated with objects that extend beyond the field of view (FOV), such as solar scenes. The system point-spread function (PSF) is modeled with a DFT and therefore has an artificial periodic feature that is inconsistent with real data. In addition, real data will be affected by resolution elements outside of the FOV due to the influence of PSF sidelobes. These edge-related problems were overcome by estimating object pixels both within the FOV and within a guard band surrounding the FOV. Using this guard-band technique, many more object parameters are estimated from the same amount of data. The optimal size of the guard band will depend upon the size of the PSF and therefore on the quality of the seeing. We have found that an appropriately sized guard band insures reliable estimates within the FOV and even into the guard band for a few pixels. A second algorithmic development involved expanding the number of estimated parameters to include

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parameters that quantify systematic errors in the data collection. Systematic errors arise with misregistration between conventional and diversity cameras and when the amount of intentional defocus is not known precisely. The systematic error parameters that we now estimate include two registration parameters and one defocus parameter. We find that we are able to estimate the misregistration to within a small fraction of a pixel width and that we are also able to estimate the amount of defocus, although object and phase parameter estimates are not particularly sensitive to small changes in defocus. A third algorithmic development involved implementing an accurate noise model. We have incorporated in our code a Poisson noise model that accommodates both the fundamental photon noise in the signal and the camera readout noise. This model is very close to an additive Gaussian noise model for low-contrast imagery, but has the advantage that signal-dependent noise expected as the contrast increases is accurately modeled. A final algorithmic development was the inclusion of a technique to suppress noise sensitivity (regularization) in the estimates. We use a method of sieves that constrains the object estimate to be spatially smoother than would otherwise be the case. We found this algorithmic development to be crucial once the guard-band pixels were introduced.

Once these algorithmic developments were in place, we were able to demonstrate both in simulation and on real solar data that near diffraction-limited imaging can be achieved with ground-based solar observations. Phase-diverse speckle data were made available to us by M. Löfdahl and G. Scharmer of the Stockholm Observatory. Images of solar granulation were collected at the 47.5 cm Swedish Vacuum Solar Telescope (SVST) on La Palma. A sequence of 100 short-exposure (20 msec) image pairs (one conventional and one diversity) was collected in a span of 30 seconds using a frame-selection technique that selects the sharpest images within the collection window. These data were collected over a spectral bandwidth of 5.4 nm centered at 470 nm. The spatial sampling was approximately 0.07 arc seconds. The diversity image was obtained with a high-quality beam splitter and a translation along the optical axis that yielded a quadratic phase error with a maximum phase lag at the edge of the aperture of -1 wave. We processed 70×70 pixel (5×5 arc seconds) subframes, which was the largest size that we felt that we could safely treat as isoplanatic. We typically processed 5 pairs of images. The reconstructed imagery is dramatically improved in contrast and resolution over any of the data images. Fine-resolution features appear in the reconstruction that are not apparent in the data images. In order to insure that we were not reconstructing false detail, we processed differing sets of 5 pairs of data images and found the reconstructions to be extremely consistent. In addition, C. Keller (NOAO), an unpaid collaborator on this effort, processed the 100 conventional images with accepted speckle-imaging techniques for comparison. We find our imagery to be consistent with but somewhat sharper than the speckle reconstructed imagery. Details of the data collection, calibration measurements, data processing, and restored imagery can be found in [1], listed in Section 3.

3. Presentations and Publications

In the first year of funding two conference presentations with proceedings and one conference presentation without proceedings were delivered. Yet another proceedings paper has already been submitted for a fourth conference presentation that is scheduled to be delivered in March of 1995. These presentations and publications are listed here in chronological order. Notice that the first paper listed received the *Best Paper Award* in the SPIE conference on *Image Reconstruction and Restoration.*

1. "Phase-diverse speckle reconstruction of solar data," J.H. Seldin and R.G. Paxman, in *Image Reconstruction and Restoration*, Proc. SPIE **2302-19**, San Diego, CA, July 1994 (recipient of *Best Paper Award*).

2. "Parameter dimension of turbulence-induced phase errors and its effects on estimation in phase diversity," B.J. Thelen and R.G. Paxman, in *Image Applications and Restoration*, Proc. SPIE **2302-23**, San Diego, CA, July 1994.

3. "Post-detection correction of turbulence-induced space-variant blur by using phase diversity," R.G. Paxman, B.J. Thelen, and J.H. Seldin, presented at the Annual Meeting of the Optical Society of America, Dallas, TX, October 1994.

4. "Simulation validation of phase-diverse speckle imaging," R.G. Paxman and J.H. Seldin, to be presented at the Optical Society of America topical meeting on *Signal Recovery and Synthesis V*, Salt Lake City, UT, March 12-17 1995.

4. Second-Year Research Plan

We are in the process of preparing two publications for submission to refereed journals. The first, an exposition of the novel PDSI technique, will be submitted to the Journal of the Optical Society of America. The second is an evaluation of phase-diversity techniques for solar-image restoration. This article will discuss our collaboration with M. Löfdahl, G. Sharmer, and C. Keller and will compare reconstructions made with conventional speckle methods, phase diversity, and PDSI. We will submit this article to the Astrophysical Journal. Our first goal is to complete and submit these publications. We are also planning a phase-diverse speckle collection at the VTT at Sacramento Peak. This collection will be relatively inexpensive since C. Keller will provide the cameras and acquisition electronics. We are interested in observing fine-resolution structure at $MgIb1$ and $H\alpha$ wavelengths. We will use 3 CCD cameras to simultaneously collect a phase-diversity image pair in a broad band and a narrow-band image containing scientifically relevant data. The narrow-band images can be deconvolved with the PSF determined by phase diversity in the broad band. In this way we hope to observe the association between filigrees and continuum bright points. This would be the first use of PDSI for "scientific" phenomenological observations. Finally, we intend to generalize PDSI to accommodate anisoplanatic effects. We will develop the generalization using simulations and, if successful, we will demonstrate the method with anisoplanatic fields using solar data. It should be easy to check performance by comparing to isoplanatic subfield reconstructions. The relative merits of an anisoplanatic reconstruction versus a mosaic of many isoplanatic reconstructions will also be investigated.